DEVELOPMENT OF CAPABILITIES OF OPTICAL DIFFRACTION ANALYSIS FOR QUANTITATIVELY COMPARING AND CORRELATING ROCK FABRICS AND FABRIC CHANGES

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Prepared by:

Howard J. Pincus — August 26, 1971
Professor Howard J. Pincus — Date
Principal Investigator

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13. ABSTRACT

Series of optical diffraction patterns (two-dimensional Fourier amplitude transforms) have been produced from photographs of rock specimens during successive stages of deformation to show spatial changes in fabric. Spatial filters and reference transforms for analysis of fabrics are being constructed from both artificial patterns and from transforms of real inputs.

A method of mapping the transforms has been developed in which the input transparency is rotated about the optic axis to yield a spoke (radial) assembly of intensity profiles.

Transforms have also been generated using partially coherent mercury vapor light as a source and a standard microscope plus auxiliary optics as the optical system.

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Rotary input gate			10	3		
Fourier transform visible through microscope eyepiece					10	0

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TECHNICAL REPORT SUMMARY

The purposes of this project are (1) to compare and correlate fabrics of suites of genetically related rocks, utilizing optical diffraction analysis and (2) to contribute to the understanding of the mechanics of rock deformation by quantifying fabric changes and relating these to other deformation parameters.

We are striving for spatial characterization of fabrics in terms that can be translated into quantitative explanations of mechanical behavior.

During the first six months of this project, we have succeeded in standardizing and making routine many of the operational procedures that formerly required more time and were less consistently reliable.

We have also pursued potentially important feasibility studies as, for example, developing the capability for recording inputs and spatial filters on small glass plates, which will permit more precise and more efficient work.

Earlier methods of mapping diffraction patterns directly on the optical bench were not efficient. Intensity profiles were not located or oriented with sufficient accuracy to permit valid comparisons between transforms of similar, genetically related inputs. A method of mapping has been developed in which the input transparency is rotated about the optic axis to yield a spoke assembly of intensity profiles; this method has the advantage of using the intrinsic symmetry of transforms to verify centering of the spoke assembly.

We have produced series of optical diffraction patterns (Fourier transforms) of photographs of specimens during successive stages of uniaxial deformation. These transforms, in turn, are being mapped with the rotating input gate described above. What all of this adds up to is the practical production of quantitative data for characterizing serially the changes in fabric of specimens as they are being deformed.

We have also established a working rock mechanics laboratory, with the capability of deforming rocks uniaxially, biaxially, and flexurally. This means that we can now generate data from our own deformation experiments.

Our work with the analysis of closed curves (i.e. contours) has given us a good start on the development of series of reference transforms to which transforms of real data can be compared.

We have also successfully produced transforms using partially coherent mercury vapor light as a source and a standard microscope plus auxiliary optics as the optical system. This approach, which in fact follows closely on Abbe's pioneering work in 1873 on microscope optics, appears to provide some possibilities for the convenient use of optical diffraction analysis in a variety of applications, especially those with microscope slides as inputs. Much of the equipment needed is already available in many laboratories.

Technical problems encountered so far have centered largely on noise in our optical system. One such source is in the pin-hole assembly through which laser light is transmitted. We have succeeded in cleaning the pin-hole adequately when necessary, but we are looking for a more reliable, more easily maintained system.

Another source of noise is in standard microscopic mounts of thin-sections of rocks when used directly as optical inputs. We expect to circumvent this difficulty by using the partially coherent light system mentioned earlier, which should be less sensitive to these noise sources than systems using coherent light.

Another technical problem has arisen in connection with the availability of adequately dimensioned and shaped rock specimens, particularly cylinders, which we have had to obtain from outside the University. However, we are on the verge of acquiring the necessary capability for finishing our own specimens to standard specifications, using equipment currently on hand at several locations in the University.

Regarding our general methodology, most of our work to date has consisted of experimentation in the optical diffraction laboratory, with supporting library and theoretical work. Toward the end of this six-month period, increasing amounts of time have been devoted to developing and operating the rock deformation experimental component of the project.

Important equipment purchased includes a Bowens Illumitran system for producing 35 mm input transparencies directly from a wide variety of transparent formats, with little chance for error in exposure and focus; this unit will pay for itself very quickly in terms of time and photographic materials saved.

We have also purchased an additional cylindrical lens to complete our complement of equipment for one-dimensional transform operations. The rotary input gate mentioned earlier was assembled from commercially available components, with a few minor modifications and additions made at the University. The system for producing transforms with a microscope and a mercury vapor light source, also mentioned earlier, was assembled entirely with equipment on hand.

During the remainder of this first year of the project, an increasing proportion of our total effort will be placed on acquisition of fabric data from rock deformation experiments.

Regarding DoD implications, all of the results achieved so far are entirely consistent with the aims of this project and the program of which it is a constituent. The spatial analysis used here contributes to the understanding of relationships between the spatial make-up of rocks and their mechanical behavior, which in turn is of fundamental importance in rock mechanics and rapid excavation. Some beneficial fall-out may develop in regard to the interpretation of contours, such as those in geophysical maps, by optical diffraction analysis.

PURPOSE OF THE PROJECT AND ITS BACKGROUND

a) Purpose

In outline, the purpose of this project consists of the following components: (1) to develop quantitative methods using optical diffraction in order to compare and correlate fabrics of rock deformation series so that changes in fabric can be related to deformation curves and other quantitative deformation data; (2) to identify and characterize through spatial frequency analysis the critical fracture parameters (surface and edge features) associated with failure; (3) to develop a system of standardized fabric patterns and reference diffraction patterns with which fabric inputs can be correlated quantitatively; (4) to develop an index of deformation in terms of fabric change, from one input to the next, and to relate this index to deformation history; (5) to develap an index of fabric heterogeneity for different directions in a single specimen, to be compared with anisotropy measures based on directional differences in physical behavior in the same specimen; (6) to compare fabrics in experimentally deformed rocks with those in several selected equivalent rocks that failed under field conditions.

In short, we are striving for spatial characterization of fabrics in terms that can be translated into quantitative explanations of mechanical behavior.

The foregoing listing indicates approximately the order in which starts are being made on each component.

During the first year of the project, work on #4 and #5 will start toward the end of the year, i.e., during the third and fourth quarters. It is expected that #6 will not pass beyond the planning stage during the first year.

b) Background - Optical diffraction analysis

Figure 1 displays flow charts for the two basic optical diffraction operations. First, through their diffraction patterns in coherent light, rock fabrics can be described quantitatively in terms of their spatial information context, viz., spacings, directions, elongations, and symmetries, regardless of scale. Second, spatial filtering can be used to suppress dominant alignments in the input so that obscure features can be detected more easily, and to aid in analyzing a mix of spatial distributions.

Figure 2 shows the basic arrangement of optical units for diffraction analysis. The diffraction pattern (two-dimensional Fourier amplitude transform, or "transform") appears in the plane of the spatial filter, where it can be photographed or mapped. Alternatively, insertion of a spatial filter results in a filtered image, as indicated in the figure.

Figure 3 shows how directional and frequency filtering can be accomplished. An idealized input is shown in (a); the spatial frequency

(inverse of spacing) of Set I is three times that of Set II. The idealized diffraction pattern (first-order) or transform of (a) is shown in (b); diffraction dots "U" and "V" are produced from Sets I and II, respectively. The removal of Set I by filtering will result in the filtered image shown in (c). This can be accomplished by proceeding as in (d) or (e). Directional filtering in (d) is accomplished by opaque (shaped) wedges that block the rays forming dots "U", but allow the rays forming "V" to pass. Frequency filtering in (e) is accomplished by blocking the rays forming dots "U" with a highcut filter (shaded), and allowing the rays forming "V" to pass through the central circular aperture.

c) Background - Rock Mechanics

It has become eminently clear that for all but very few rocks the classical models of ideal isotropic elastic and plastic bodies are not valid. In the attempt to explain rationally the complex mechanical behavior of many rocks, increasing attention has been given to identifying the relationship between fabric and mechanical behavior. Such identification, when successfully accomplished for a wide variety of rocks, will contribute to more reliable predictions of rock behavior and more confident interpretation of stress history from fabric studies.

Fabric studies performed to date have yielded both quantitative and qualitative results, many of which have been achieved only after very tedious work. Some analytical fabric studies include a subjective element that makes somewhat dubious the validity of comparing or pooling results based on work by different operators. However, there is little doubt that fabric analysis has already achieved useful results, and its future promise is unquestionably great.

The experimental techniques required to produce deformation suites of rocks for this study are well established in the field of rock mechanics. Standard uniaxial, biaxial, and triaxial loading will provide the bulk of the input data. In addition, cantilever and third-part loading, as used by the principal investigator in earlier studies, will also provide input data. Series of fabric inputs from deformation experiments plus series of artificial inputs will provide the main kinds of input data to be operated on.

TECHNICAL PROBLEMS ENCOUNTERED

a) For awhile, an apparently irremediable source of noise in the optical system seemed to defy correction. Among many inspections made in the search for the source of trouble, the pinhole assembly was examined and appeared to be free of dust. Cleaning of the pinhole with a low-pressure inert gas jet removed this trouble for awhile. It has proved necessary to repeat this cleaning, and also to clean the laser windows. We are attempting to keep the dust level in the laboratory as low as is feasible, and we are also exploring the possibility of replacing our pin-hole assembly with another manufacturer's product which facilitates both cleaning and replacement of pinholes.

b) Another unit we hope to improve also involves a pinhole. The versatility of the photoelectric scanner, used for mapping transforms, is somewhat hampered because the size of the pinhole is fixed. Although some flexibility is available by changing the size of the transform optically, such flexibility is attainable only inconveniently. We are now planning to develop hardware that will permit easy replacement in the scanner of pinholes of different sizes.

c) It has been necessary to experiment with a variety of photographic emulsions and processing parameters to obtain suitable optical densities and density contrasts in input transparencies and special filters. Such densities and density contrasts have been achieved. However, we find that some results in working with film are not always as good as those presumably obtainable with glass plates. We find that off-the-shelf hardware for handling plates with the properties we desire is just about unavailable. However, we are developing a procedure for mounting 2" x 3" holographic plates in 4" x 5" sheet-film holders that will almost certainly be reliable and efficient.

d) A major operating problem that still confronts us relates to the generation of noise by inputs consisting of microscopic mounts of some thin-sections of rocks. We believe that the difficulty arises from surface topography of the rock slices. We did think at one time that phase shifts and spurious refraction generated by curvature in the cover glass were responsible, however subsequent experimental work has led to our abandoning that view. We are now developing the capability for working with partially coherent light (Figure 8 and related discussion) which should yield improved results for standard thin-section mounts.

e) At this point, we are still dependent on external sources for the production of precisely dimensioned and shaped cylindrical rock specimens for deformation experiments. We are, however, rapidly moving toward self-sufficiency in this regard with equipment on hand at several locations in the University.

GENERAL METHODOLOGY

To date most of our work has consisted of experimentation in the optical diffraction laboratory, with suitable back-up and exploration in library work (see Appendix A) and checking of observations through the theoretical route.

The laboratory work has been done with the C-120 Laserscan system and accesories in the principal investigator's laboratory. Figure 4 shows the optical bench configuration for TV monitoring of the spatial filtering operation. With this set-up, real-time spatially filtered outputs are provided as filter parameters are varied.

Figure 5 shows the optical bench configuration for mapping the transform with a spot scanner. The output of the scanner is plotted as a profile on an x-y recorder, some results of which are discussed later and are displayed in Figure 7. Direct scanning on the optical bench is superior to the scanning of a photograph in terms of speed, linearity, and signal-to-noise ratio.

Photographs of rocks from suites of experimentally deformed specimens were obtained initially from the Twin Cities Mining Research Center. We are now producing such inputs on this campus.

Some time has been invested in improving techniques for producing specialized types of spatial filters, and in improving the quality of both inputs and outputs. These activities are part of the continuing improvement of our techniques as we carry on our research. Recently much effort has gone into expanding our capabilities for testing mechanical rock properties. Much of the properties testing equipment required for this project is already on hand, hence the major effort has been in deploying this equipment and in training personnel to achieve an efficient operation.

IMPORTANT EQUIPMENT PURCHASED OR DEVELOPED

a) We have purchased a system (Bowens Illumitran) which we are using for producing 35 mm input transparencies directly from a wide variety of transparent formats, with little chance for error in exposure and focus. In the short time that we have had this unit we have realized savings in both time and film. We have also obtained the necessary information for ordering minor accessories that will permit our photographing opaque formats, although the system was not designed for that option.

b) We have purchased a 60 mm plano-convex cylindrical lens and mount to augment the cylindrical lens already on hand. With a single cylindrical lens one can produce one-dimensional transforms; with the second cylindrical lens we can undertake spatial filtering that will be particularly advantageous in working with certain fabrics, e.g., those with highly preferred orientations.

c) From commercially available components purchased earlier we have assembled an input gate that is capable of rotation as well as horizontal and vertical linear translation (Figure 6). All three motions are vernier-controlled. The rotation range is unlimited. We have developed a simple but effective procedure for mounting input film in liquid and rotating and translating the entire unit. The rotary capability of the input gate greatly enhances the profiling of transforms, as indicated in the test pattern in Figure 7, upper right. By rotating the input we can produce a series of profiles across the transform with a scanner that has only one translational motion. Further, the radial arrangement of profiles has some conspicuous advantages over parallel profiles: mapping is concentrated toward the center of the transform, and symmetry of the transform about its center provides a ready check for spurious results because each profile should also be symmetrical about its own center. From a set of calibrated radial profiles a contour map of the transform can be generated.

d) Using equipment already on hand, we have succeeded in producing transforms with a microscope and partially coherent illumination (Figure 8). This follows closely on Abbe's pioneering work in 1873 on optical

transforms in microscopes. A spectrally (color) filtered Hg source provides 5461 Å illumination, which is condensed and passed through a pin-hole. The light is then collimated and passed through the input on the microscope stage. Unlike Abbe's model, here the transform is directly visible through the eyepiece. Our system uses relatively easily available components and is less sensitive to some optical imperfections than systems using more coherent light. We expect to use this system for either the direct study of transforms of thin-sections of rocks or of contact-transparencies of thin sections. We have not yet attempted spatial filtering with this set-up, but there are no technical reasons why this cannot be achieved. Our equipment is still in the breadboard stage, and many slides of thin-sections of rock seem to be overabundantly endowed with optical aberrations, but this approach is bound to yield at least some useful results (Summerfeld, 1954).

e) We are currently investigating the purchase of a laser power meter, to be used not only for determining the optical power input to our C-120 system, but also for power measurements at locations such as transform planes. The power meter will provide a means for calibrating data such as transform profiles which we now calibrate on a relative scale by indirect methods.

TECHNICAL RESULTS

During the first half-year of this project's operations we have spent much of our efforts in improving and refining our techniques, and in standardizing many of our operational procedures. We have also invested effort in feasibility studies that have yielded new insights as well as improved techniques. During the second quarter we started generating substantive research results, *per se*, and during the last part of the second quarter our own facilities became operational for conducting rock deformation experiments of the kind needed in the project.

Figures 4 - 16 and their captions essentially convey the scope of our activities. Figures 6 - 8, discussed earlier, deal with some of our developmental work.

The spatial frequency analysis of fabrics requires several approaches, one of which is to filter selectively inputs made up of unresolved mixes of spatial frequencies. Earlier, before the project was officially underway, we had prepared sets of spatial filters consisting of simple geometric figures such as circles, circular rings, ellipses, and the like. We have since prepared the filters shown in Figure 9, some of which can also be used as standard transforms to which to compare transforms generated by real inputs. These patterns can be inserted in the transform plane at different effective sizes by changing optically the relative size of the incident transform or by inserting photographically enlarged or reduced transparent replicas of the original patterns. The collection of artificial transform-filters will be enlarged continually as we collect additional series of transforms from deformation suites and learn to distinguish the common spatial elements in particular types of series. In brief, these patterns are tools developed

from the research itself; the patterns we draw six months from now are likely to be substantially different from today's patterns.

Also as part of analysis by filtering, we have worked on procedures for subtracting one input from a similar input, as for example, in looking for changes from one photograph to another in a deformation suite. We are attempting to do this by inserting the photographic negative of the transform of the "before" photograph in the transform plane of the "after" input. To explore the feasibility of such subtraction and to begin to evaluate results the pair of test pattern sets shown in Figure 10 have been produced. Results so far have not been encouraging, but we do not believe that we have as yet made a fair test. We believe we can perform a better test when the "before" transform is recorded directly on a glass plate that can be reinserted in the optical path in the position and orientation in which it was recorded. We expect to achieve this capability soon. We will also try other pairs of patterns that will more nearly resemble or in fact be real inputs. Should our subsequent procedures not work satisfactorily, we will then switch to the method of the holographic transform where phase as well as amplitude information is recorded and by which subtraction has been accomplished elsewhere (Monahan, et al, 1969). For the present, however, we would like to see how far we can go with the simpler, "amplitude only" method.

We have also produced transforms and filtered images of genetically related contour maps (polynomial surfaces of different orders, regional gradient and anomaly maps) to investigate further the transform properties of families of closed curves (Figure 11). Interaction effects from some inputs turned out to be more complicated than anticipated, but explaining these complications has in turn shed light on other problems. A paper was presented on these results at the national meetings of the Society of Photographic Scientists and Engineers in Chicago on April 23. With the encouragement of an editor of an international journal, we are preparing a version of this paper for publication.

The results obtained from working with families of closed curves is a logical precursor to working with intersecting and branching curves, networks, and the like. All of these basic configurations are inherently part of the makeup of rock fabrics, and must be looked at in terms of both idealized and real data. This work will also contribute materially to the building of a collection of reference or standard transforms, discussed earlier.

All of the foregoing discussions, on Figures 1 - 11, have been concerned explicitly with optical diffraction analysis, per se. Figures 12 - 16 are concerned with rock deformation experiments that will yield information to be processed optically.

We are assembling diffraction patterns from suites of specimens of deformed rocks. To do this in a systematic way, we have established conventions for marking, scaling and photographing rock specimens during deformation experiments (Figure 12). We are also laying the groundwork for obtaining inputs from specimens impregnated with fluorescent dye penetrants to highlight fracture propagation during deformation experiments, and for non-photographic recording of fabrics through the use of acetate peels on specimen surfaces.

Several types of deformation experiments are either underway or will be underway within the fortnight. In all experiments, fabric changes will be recorded at no load and at successively higher loads during incremental loading.

Work has started on uniaxial deformation of cylinders. We will also deform cylinders biaxially (radial compression) as soon as appropriately prepared specimens are available.

Fabric changes will also be recorded in cantilever and third-part loading of rock slabs and rock slices cemented to aluminum bars (Pincus and Gardner, 1968) (Figure 13). Work with rock slices has started as this report goes to press. Calculations are underway to determine optimum ranges of thickness of slices.

Some of the facilities for performing the above experiments are shown in Figures 14 and 15. During the coming year we will also conduct cyclic loading experiments, and hope to move by the end of the year into triaxial experiments, which will require a different approach to fabric recording and increased availability of finished cylindrical specimens.

We plan to concentrate on rock types represented in the standard suite designated by the Twin Cities Mining Research Center for the ARPA project, on some of the rocks in the Twin Cities-NASA simulated lunar rock suite, and on several other rocks of special interest in fabric studies. We have already made our request to Twin Cities for representatives of the ARPA suite and we have on hand a fairly complete set of the NASA rocks, with thin sections prepared in our own department.

Figure 16 shows one set of results obtained so far from uniaxial deformation. The transforms produced will be mapped by the method illustrated in Figure 7, to provide quantitative evaluation of spatial frequency changes during deformation. A cursory examination of the transforms in Figure 16 shows the most conspicuous change, detectable by eye alone, occurring at low load levels, i.e., from (A) to (B). Higher spatial frequencies (more closely spaced lineaments) make their appearance in (B). Close examination of the input photographs shows the development in (b) of a faint mottling in the light-colored (feldspar) areas that carries through to (c), and which might account for the higher spatial frequencies in (B) and (C). Other changes in the transforms that seem to affect their inner (low-frequency) regions will have to be checked by scanning, as in Figure 7.

In conclusion, as this report is being assembled, we are beginning to crank out fabric data susceptible to study by optical diffraction methods refined for this purpose.

IMPLICATIONS FOR FURTHER RESEARCH

An essential step in future operations will be to determine which features in each series of input photographs is associated systematically with progressive changes in the diffraction patterns. From this, we will search for covariations between diffraction patterns and deformation (stress-

strain) curves; if such covariations are found, we will attempt to characterize them quantitatively. The next step beyond this will be to quantify relations between changes in input features (grain size, grain elongation, microfracture spacing, etc.) and deformation curves.

SPECIAL COMMENTS

We are also looking at the diffraction patterns of drawings and photographs of groups of discrete, separated particles of different shapes and sizes to determine empirically the effects of different configurations, shapes, spacings, and sample size.

As the particles are "moved" toward each other and ultimately come in contact they achieve the spatial configuration of some rocks.

CONCLUDING REMARKS

Work with both artificial and real inputs has yielded useful results, and indicates that the next steps contemplated are indeed the appropriate ones to follow.

It is clear that the capabilities of the major items of equipment on hand and the technical skill of the personnel involved are equal to the major tasks currently before us.

During the next six months increasing emphasis will be placed on acquisition of fabric data, *per se*, as we move into an expanding program of experimental rock deformation.

Further refinements of optical diffraction analysis will be undertaken as required by needs arising from our generating additional fabric inputs.

APPENDIX A

Figures Accompanying Text

(Nos. 1-16)

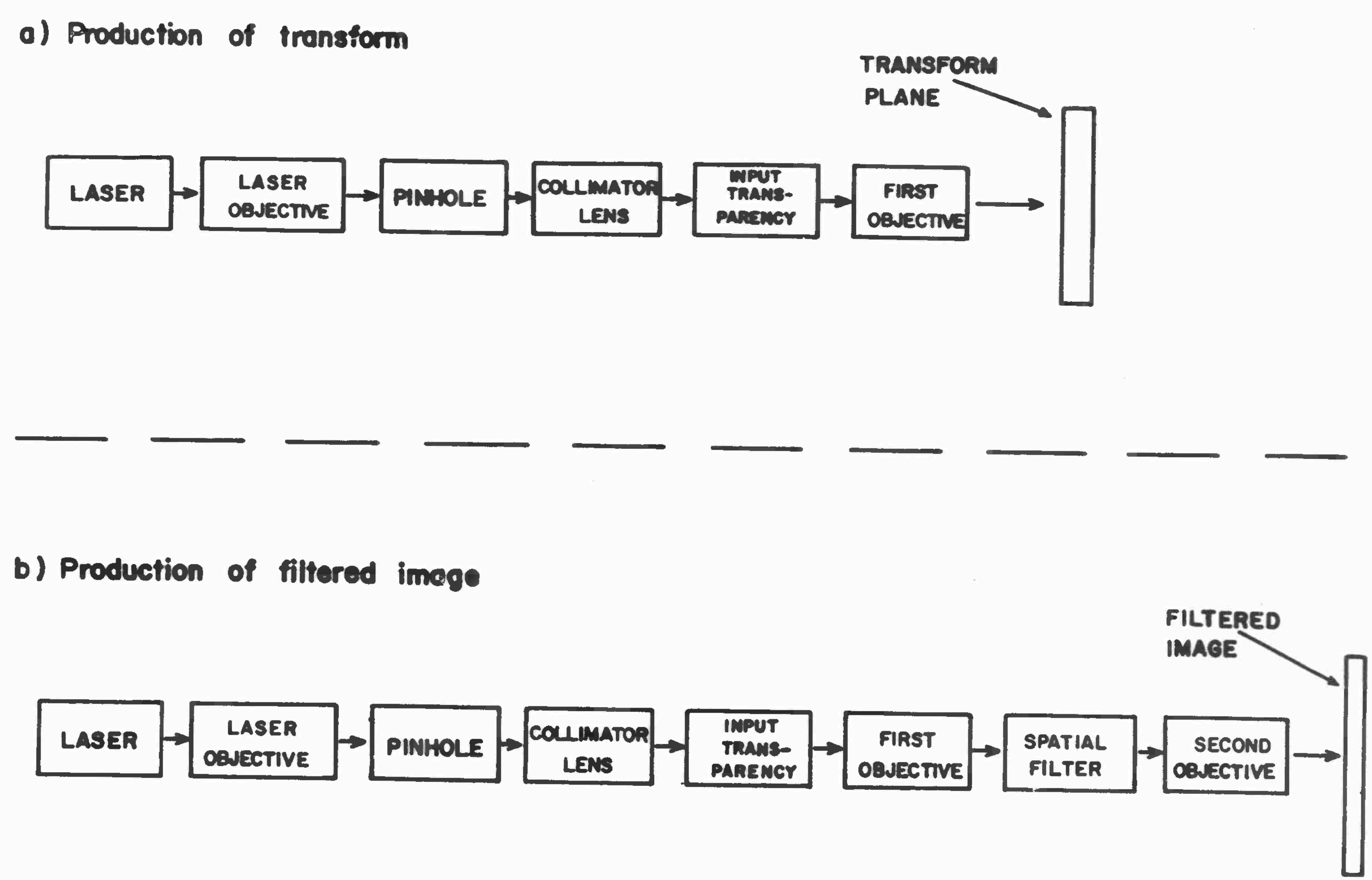


Figure 1 - Flow charts for the two basic optical diffraction operations. (from Pincus, 1969b)

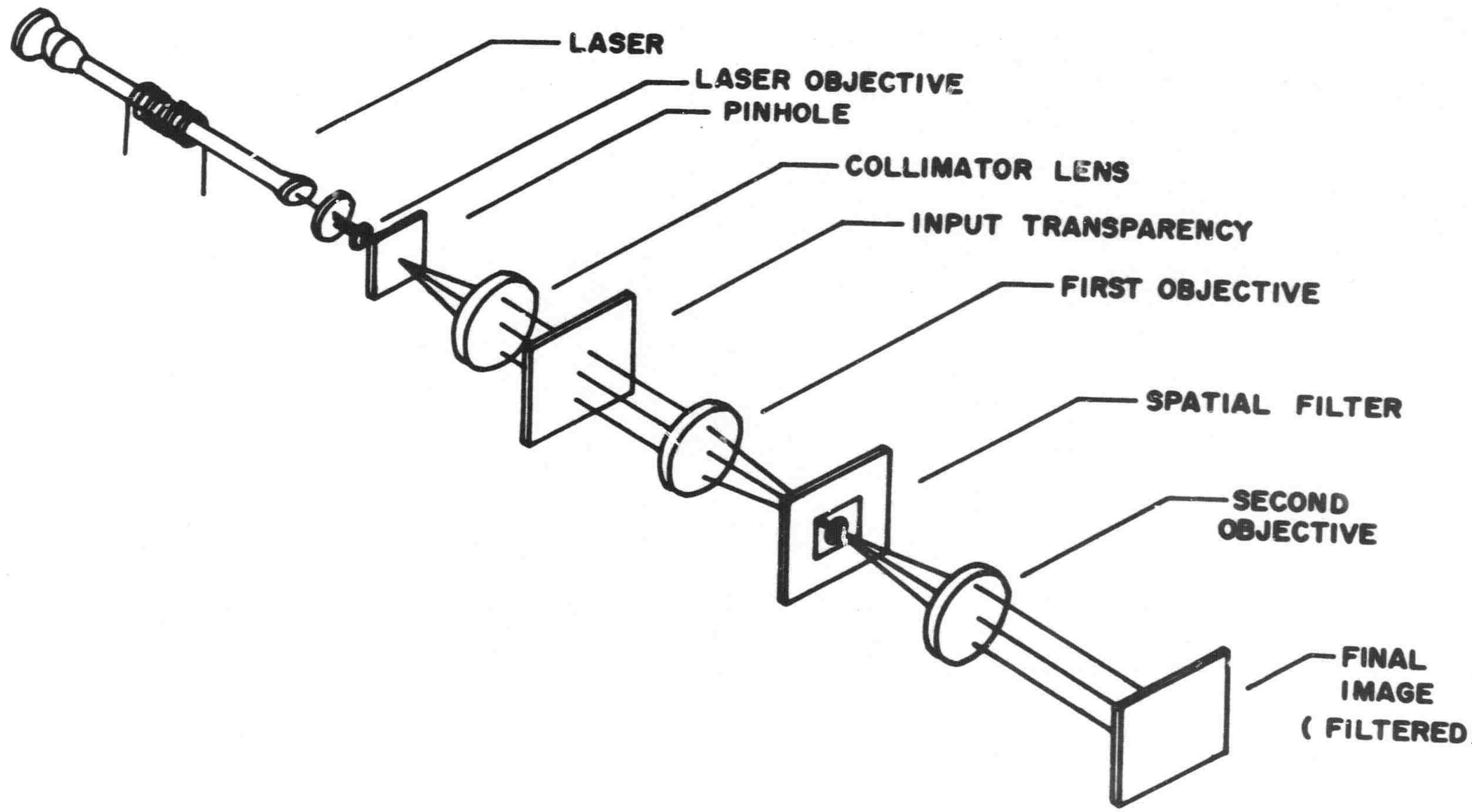


Figure 2 - Schematic diagram for optical diffraction analysis (from Dobrin, Ingalls, and Long, 1965, Figure 16)

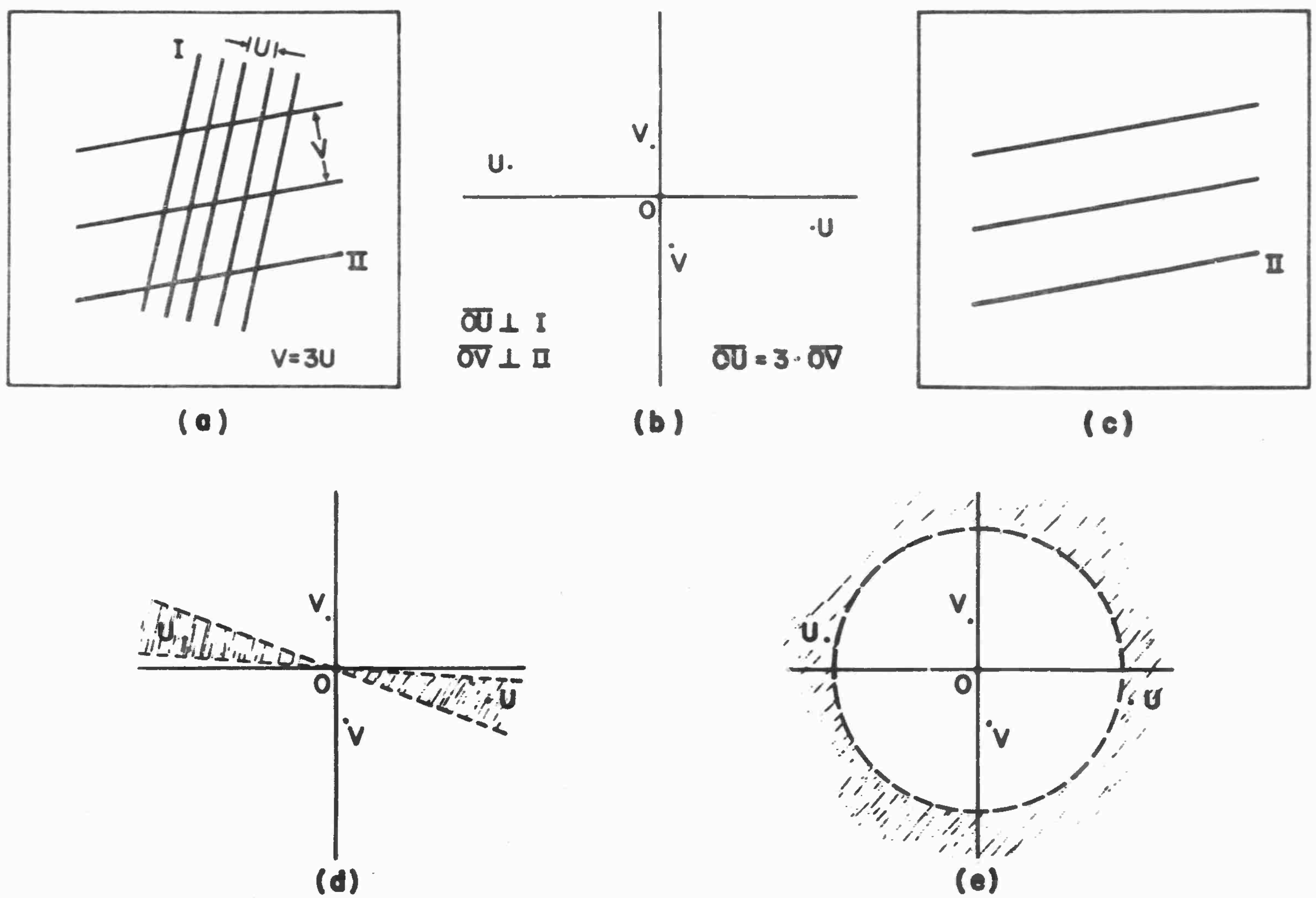


Figure 3 - Directional and frequency filtering (from Pincus, 1969b)

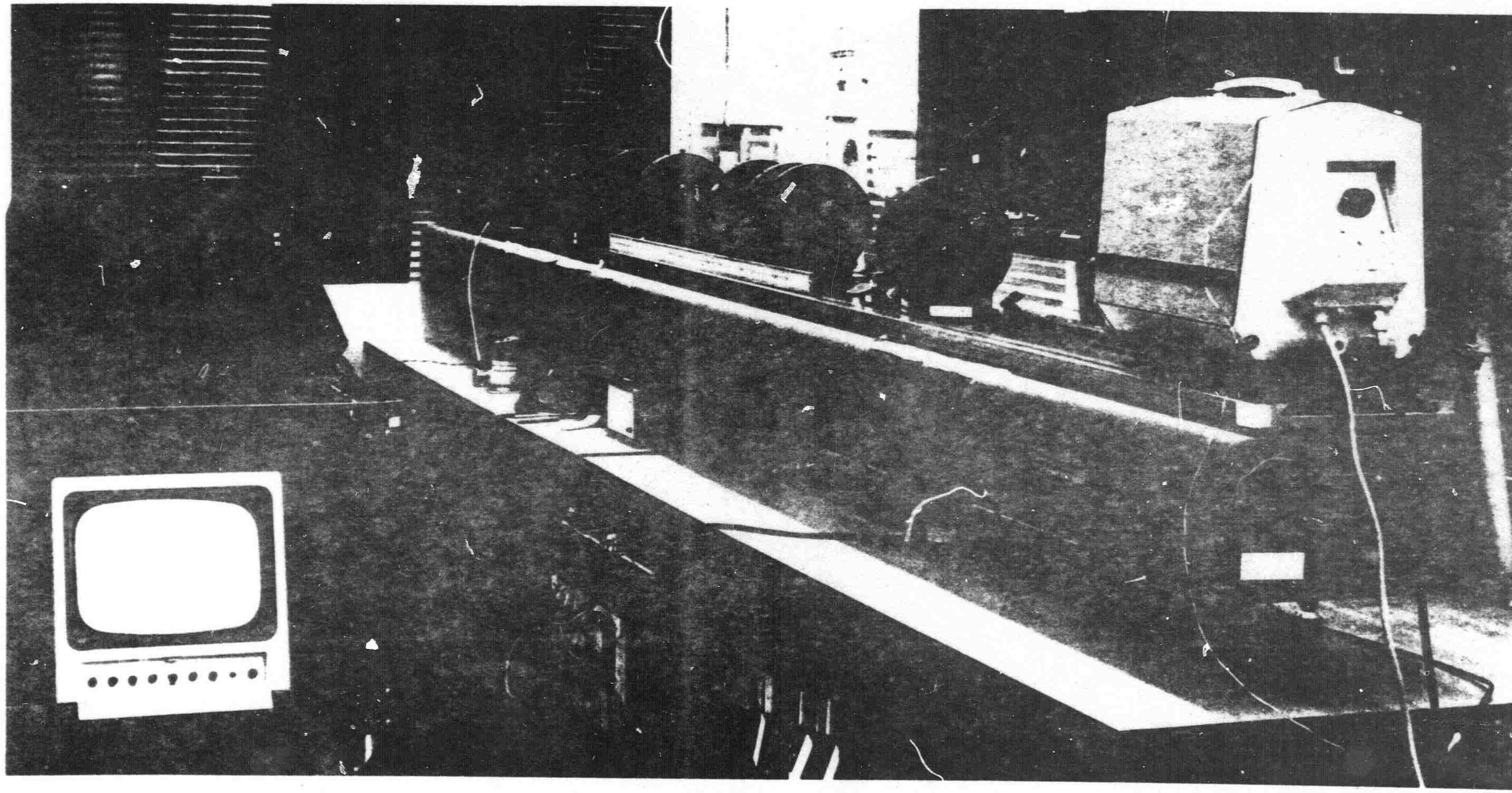


Figure 4 - Optical bench configuration for TV monitoring of spatial filtering. Directional filter is located about midway along the bench. Laser is at the far end and TV camera at the near end. Scale: Meter stick on outer track of bench.

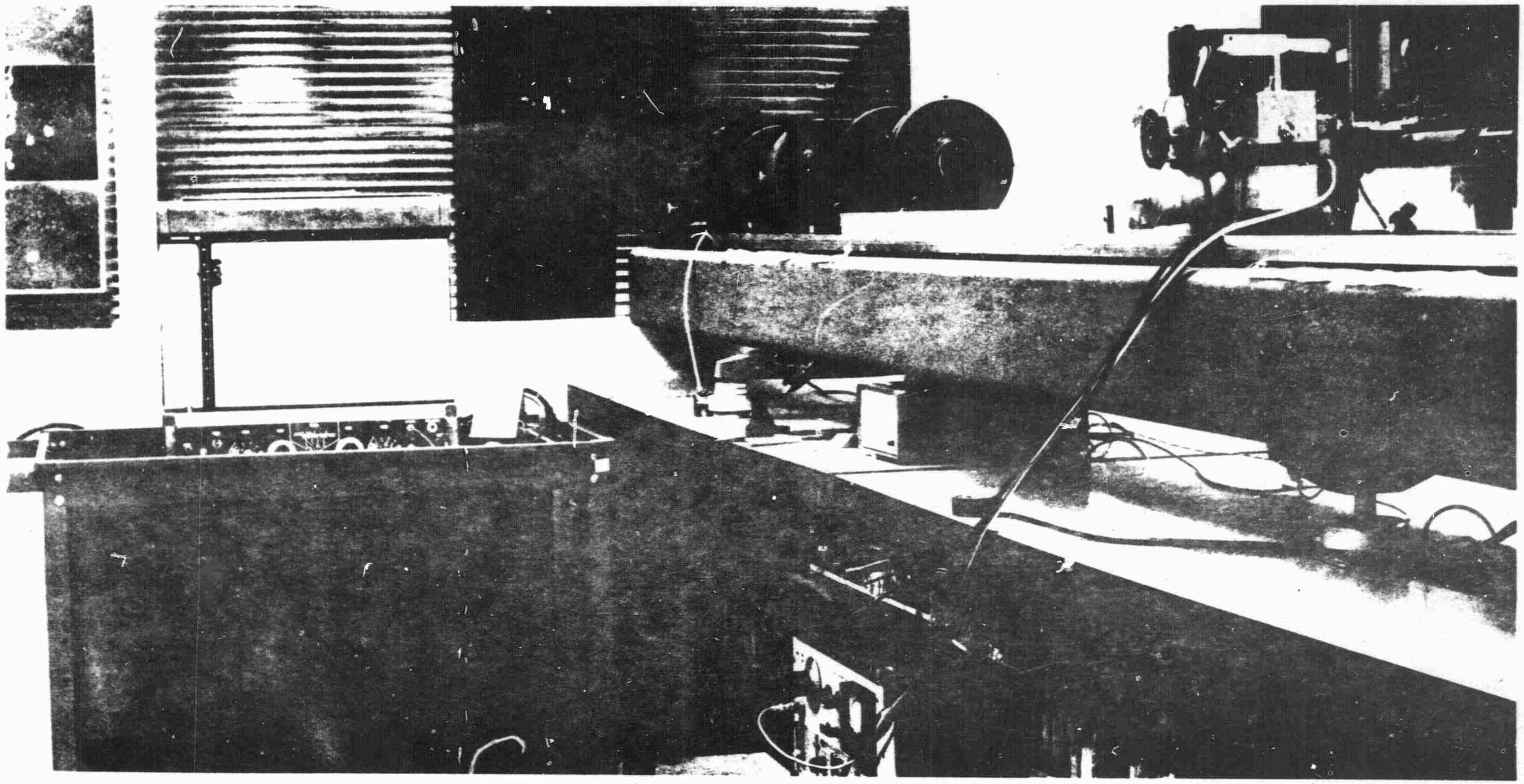


Figure 5 - Optical bench configuration for scanning the transform (diffraction pattern). Scanner is at near end of bench. Output is displayed on X-4 plotter in left background. Scale: Meter stick on outer track of bench.

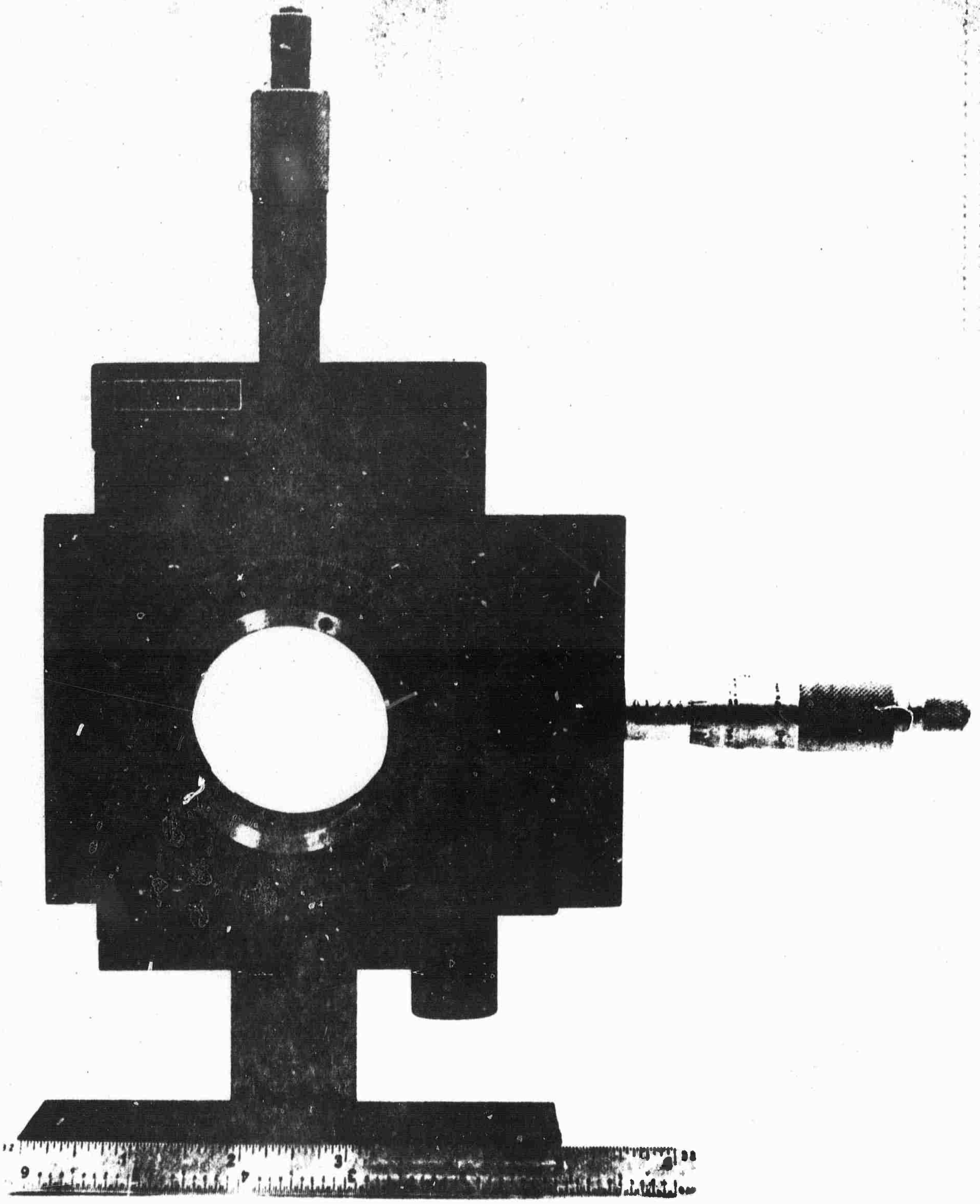


Figure 6 - Rotary input gate. Black knob projecting below right corner of stage provides rotation. Liquid-filled sandwich (not shown) of two optical windows and input film are secured with springs or rubber bands to the four prongs protruding from the inner polished sleeve. Scale: Base is 5 in. (127 mm) wide.

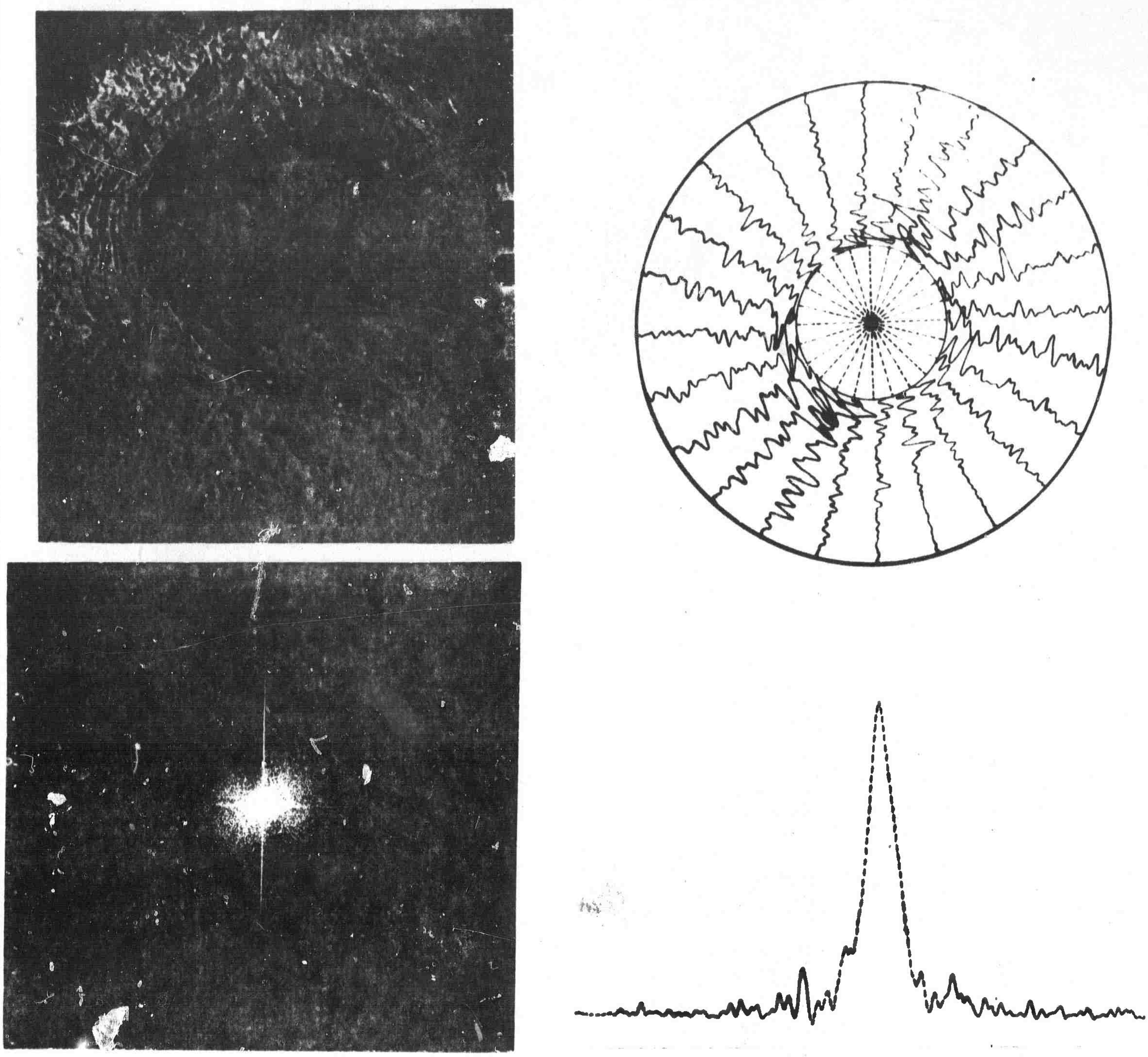


Figure 7 - Upper right, assembled radial profiles of transform. Input at upper left is aerial photo of El Solitario Dome, Presidio and Brewster Counties, Texas. Transform of input (from Pincus, 1969b), at lower left, shows wedge-shaped dark areas (centered at 11 o'clock and 5 o'clock orientations) resulting from selective shadowing of lineaments in the input. Radial assembly at upper right shows profiles through transform at 15° intervals, with central and outer portions of each profile deleted. Typical profile appears at lower right, with dashed sections indicating those portions deleted from the radial assembly; this profile appears in the radial assembly in the 9 o'clock - 3 o'clock orientation, with the left portion inverted.

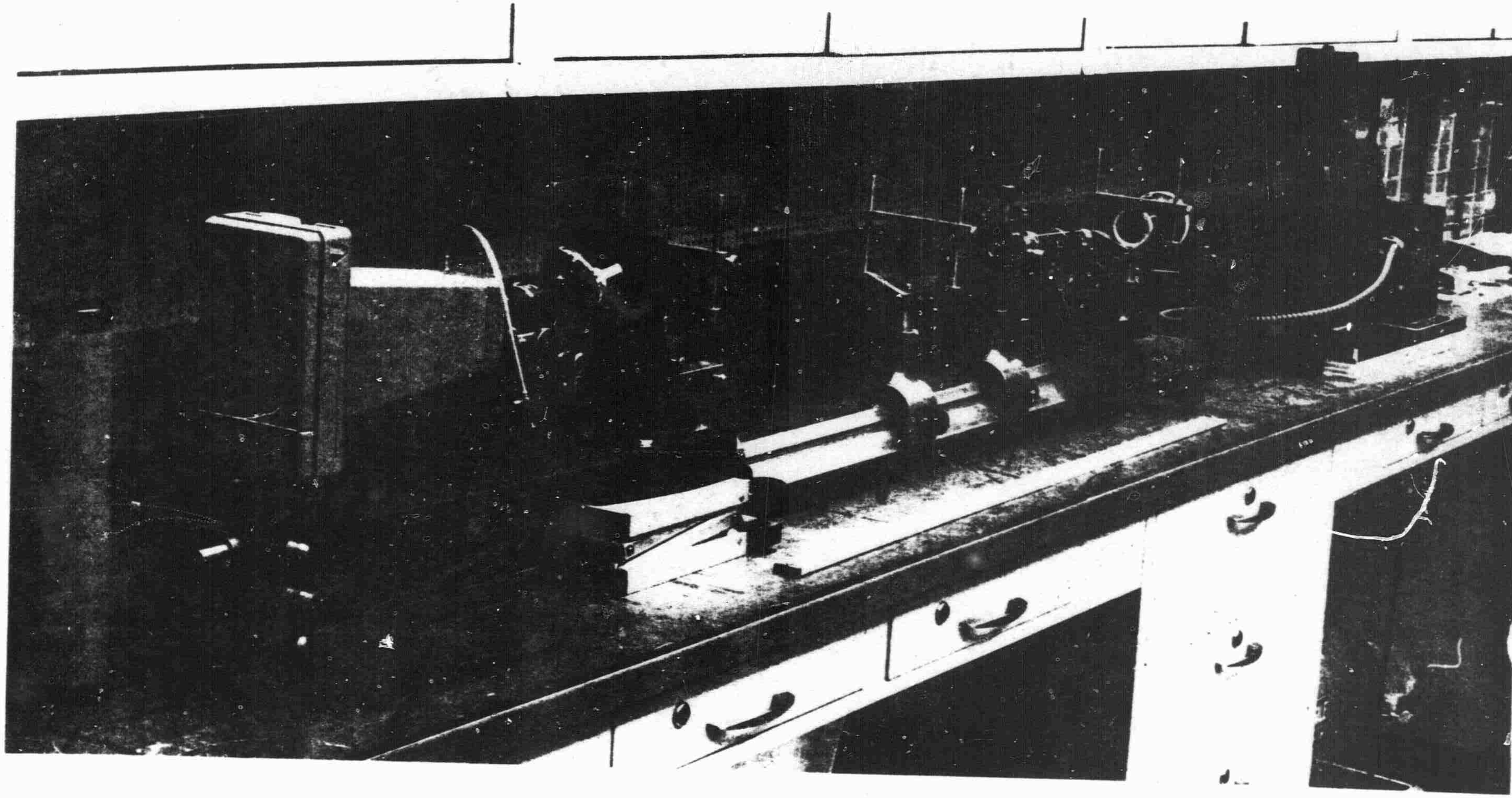


Figure 8 - Configuration for obtaining transform with Hg-vapor source and microscope. Light source is at far end of the bench. Transform-generating microscope and camera are at near end of bench. Scale: Meter stick, right-center middleground.

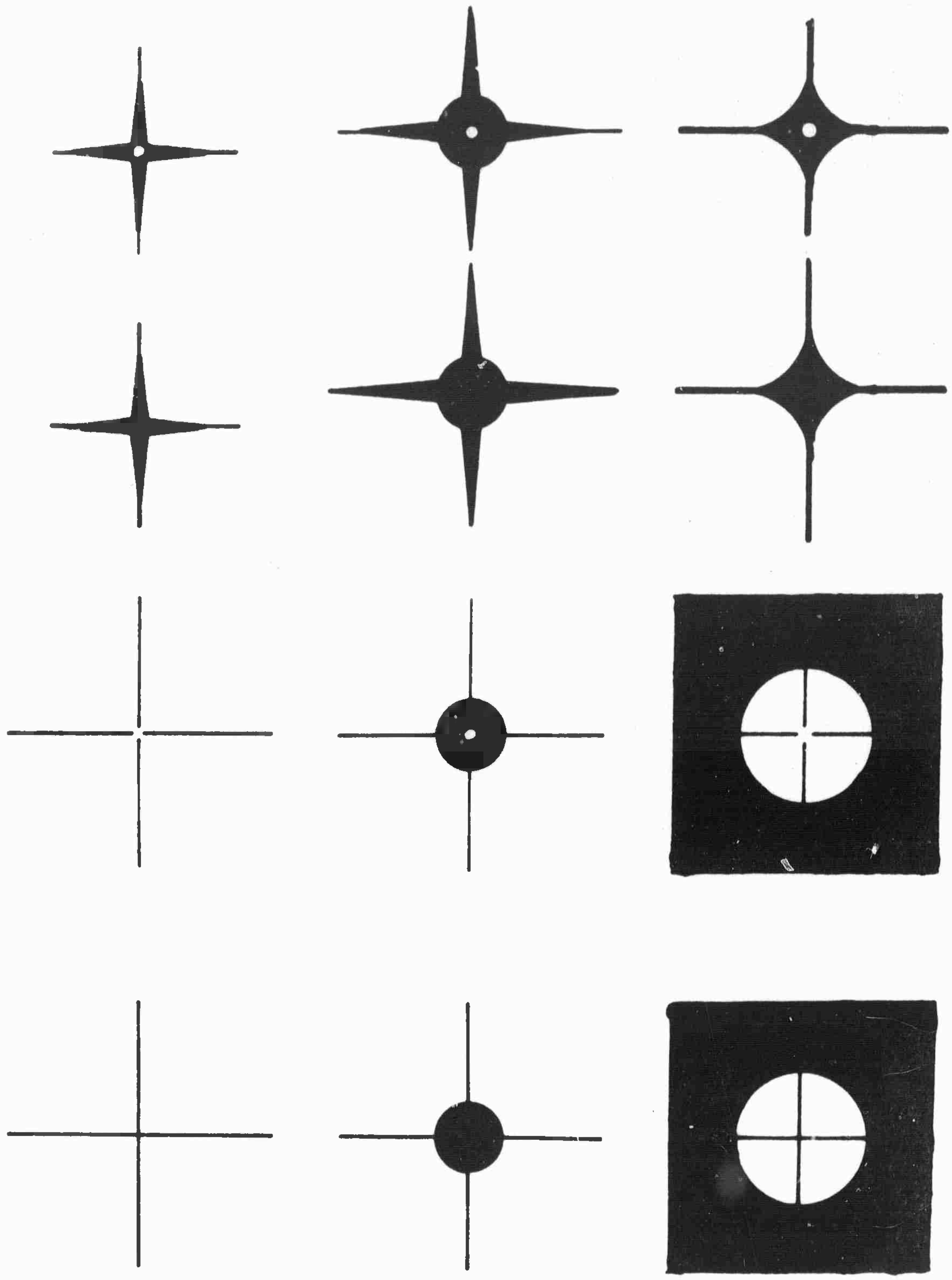


Figure 9 - Artificial transforms and specialized spatial filters. These figures are inserted in the transform plane to delineate gross properties of transforms and their inputs and to produce filtered outputs. Drawings in second and fourth columns from the left are equivalent to the drawings immediately to their left (first and third columns) except for a clear central spot (d.c. and very low frequency pass).

1A

1B

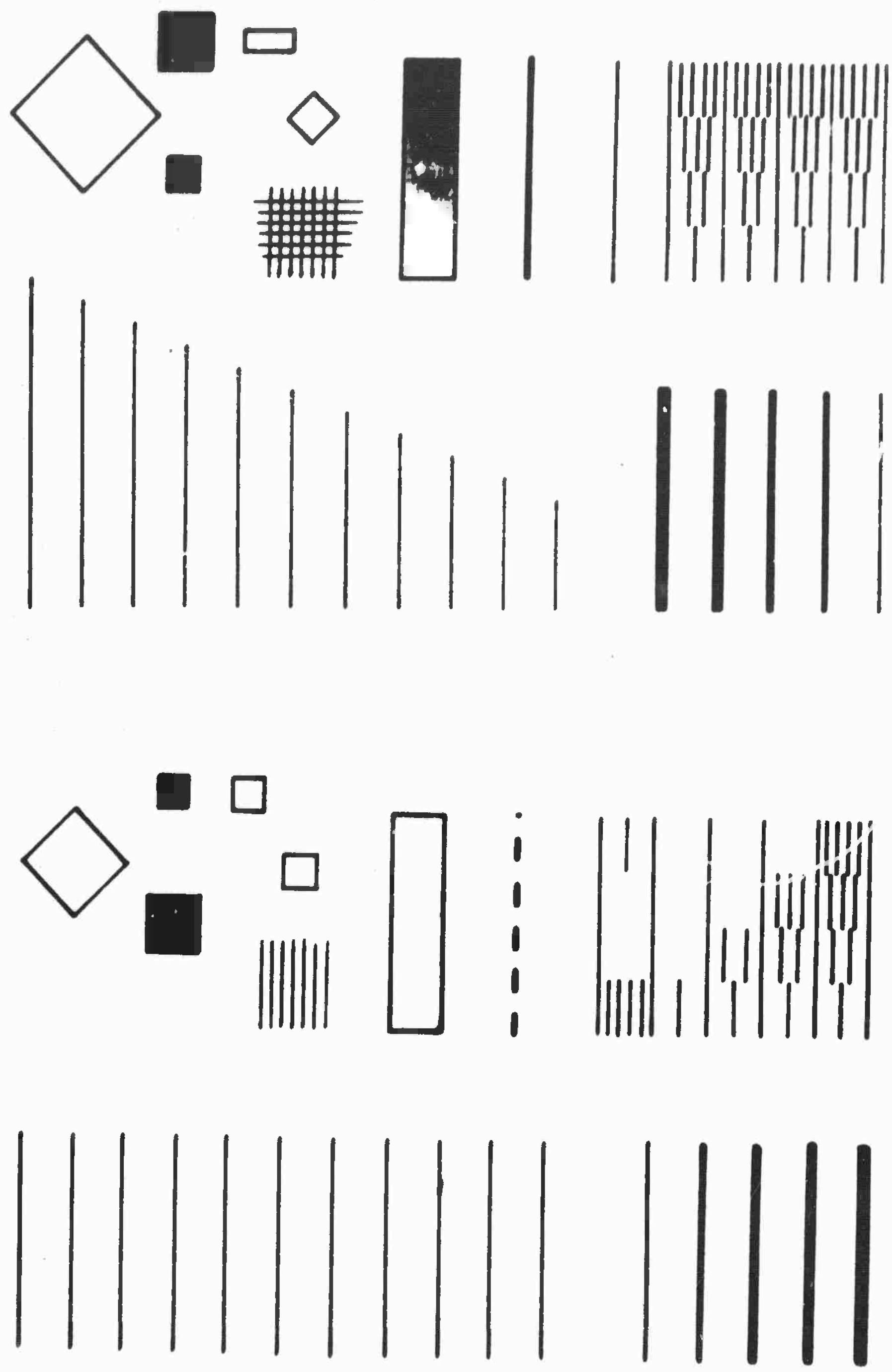


Figure 10 - Pair of test pattern sets for filtering experiments in which components from one set of patterns are to be subtracted from their counterparts in the other set of patterns. Thus, subtraction of the solid black square in the upper left of test pattern set 1B from the larger solid black square in the corresponding position in set 1A should yield a hollow square.

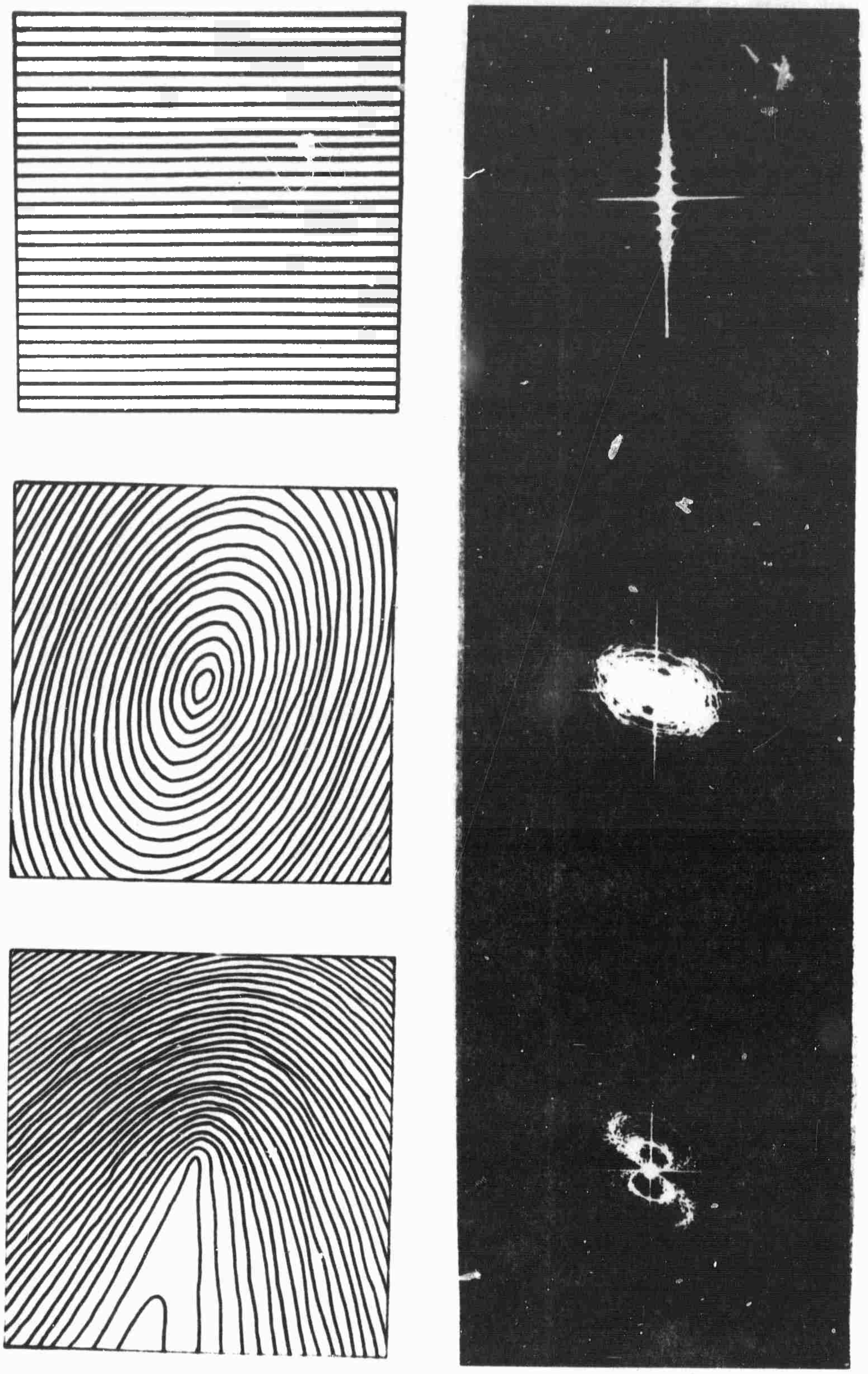


Figure 11 - Sets of closed curves and their transforms. If the top set of curves are contours on an inclined plane and the middle set are contours on elliptical "hill" elongated NNE-SSW, the bottom set display the sum of the above two sets. Note that the closed curves in the bottom transform have the same general shape as both the middle input and its transform, with a 90° rotation from the former.

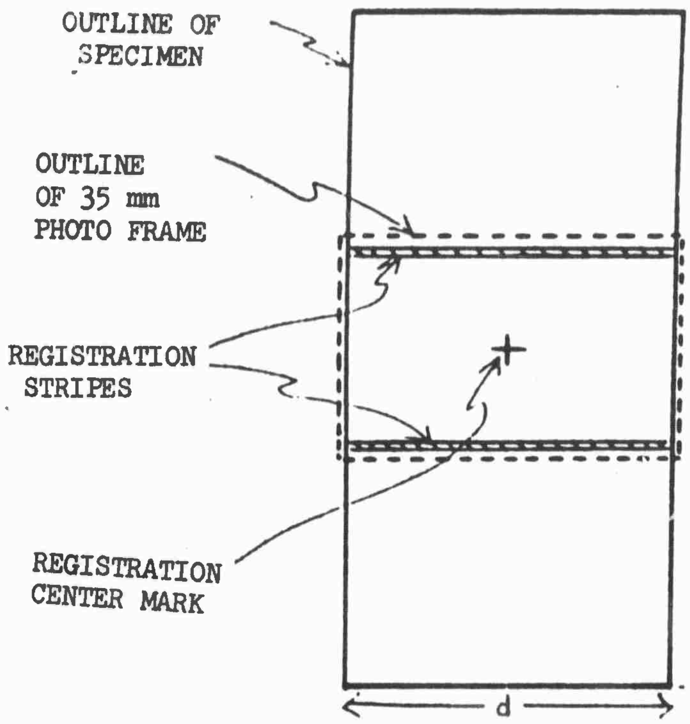
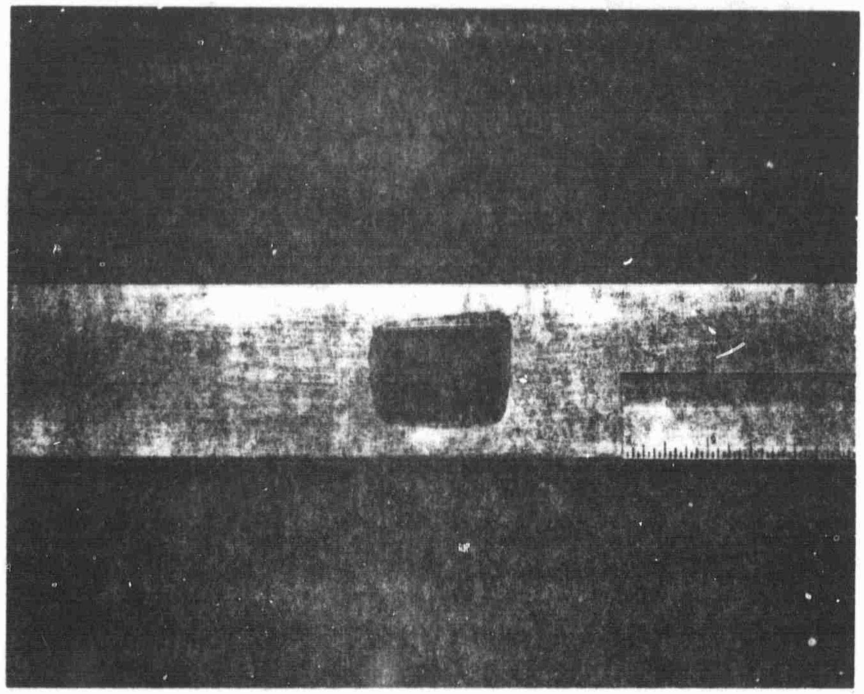


Figure 12 - Marking of cylindrical specimen for uniaxial testing. Center mark is at center of vertical axis and midway between registration stripes. Spacing between registration stripes is between 1/2 and 2/3 specimen diameter (d). Before loading, strip of millimeter paper (1/2 circumference x 1 cm) is taped to front of specimen between registration marks, photographed, and then removed. Minimum size 35 mm frame is shown.



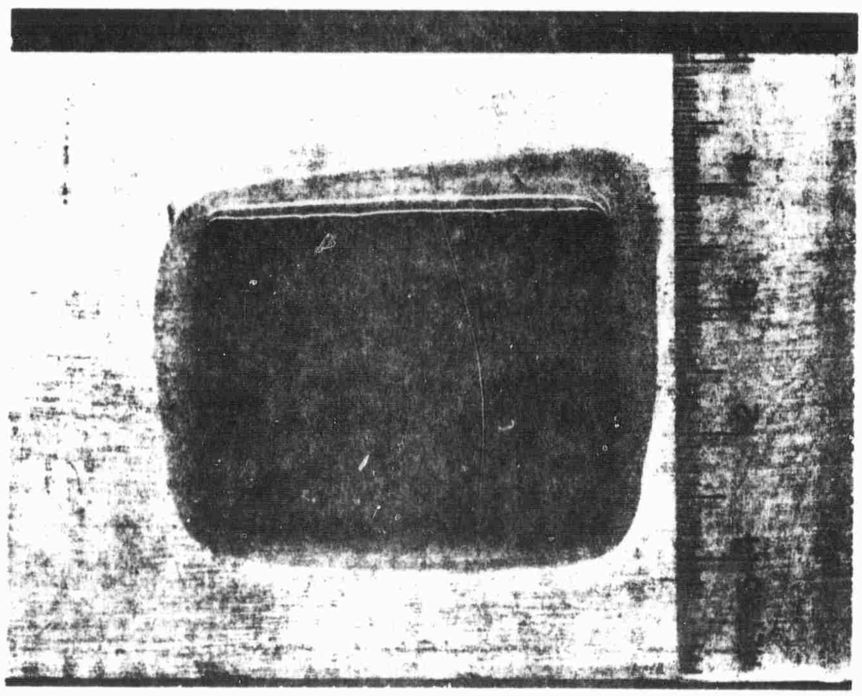
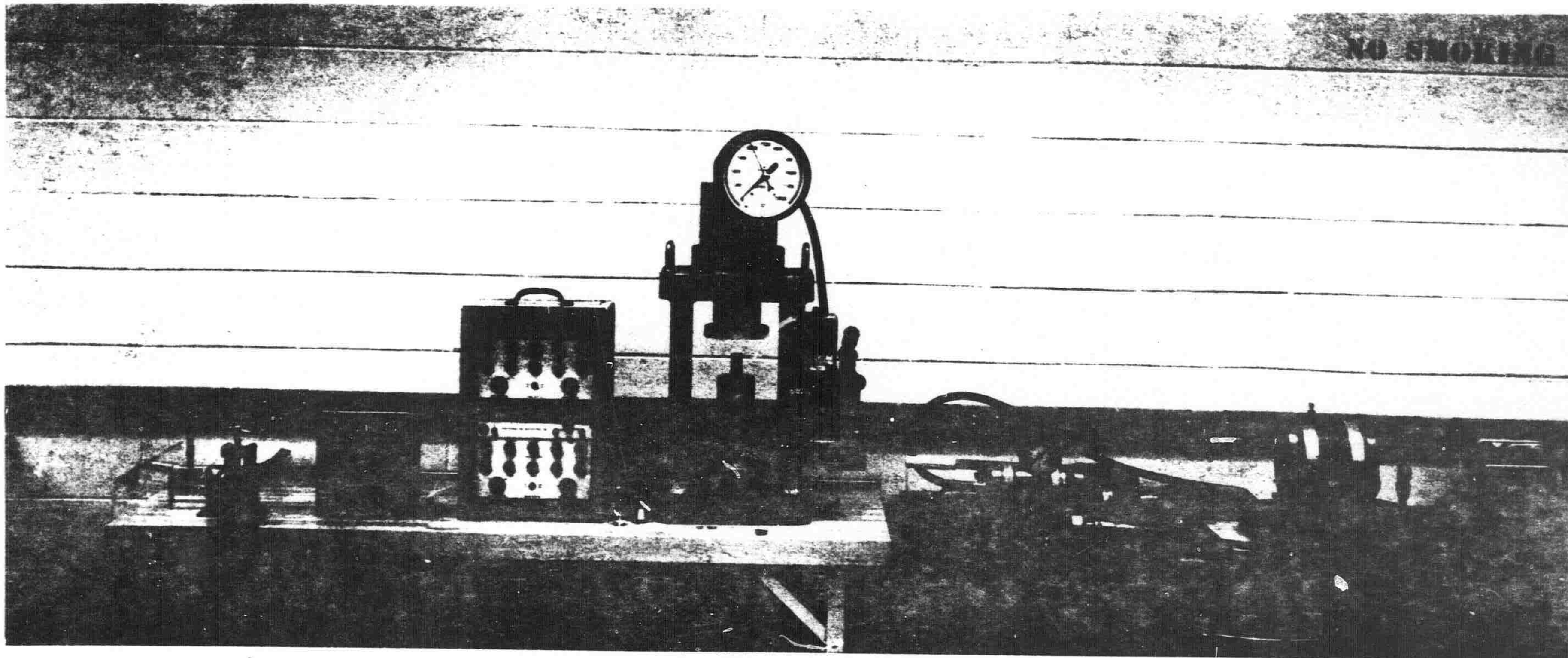


Figure 13 - Mounting of rock slice on aluminum baı for cantilever and third-part loading experiments. Scale: Bar is 10-1/8 in. (app.) x 2 in. x 1/4 in. (257 x 50.8 x 6.35 mm)



a b c d e

Figure 14 - Some of the equipment available for deformation of cylinders, slices and slabs. a) Micrometer loading frame for cantilever deflection of 1/4 in. (6.35mm) aluminum bars and 1/2 in. (12.7mm) rock slabs. Deflection is accomplished by strain increments. b) Vise mounted loading arrangement for same bars and slabs as in a). Deflection is accomplished by load increments. c) Loading apparatus (Soiltest CT-710) for uniaxial loading of small cylinders. d) Biaxial loading apparatus for NX cores (2-1/8 in. app. or 54 mm diameter). e) Biaxial loading cell for 5-5/8 in. app. (143 mm) diameter cores.
(Not shown is third-part loading apparatus for aluminum bars and rock slabs.)

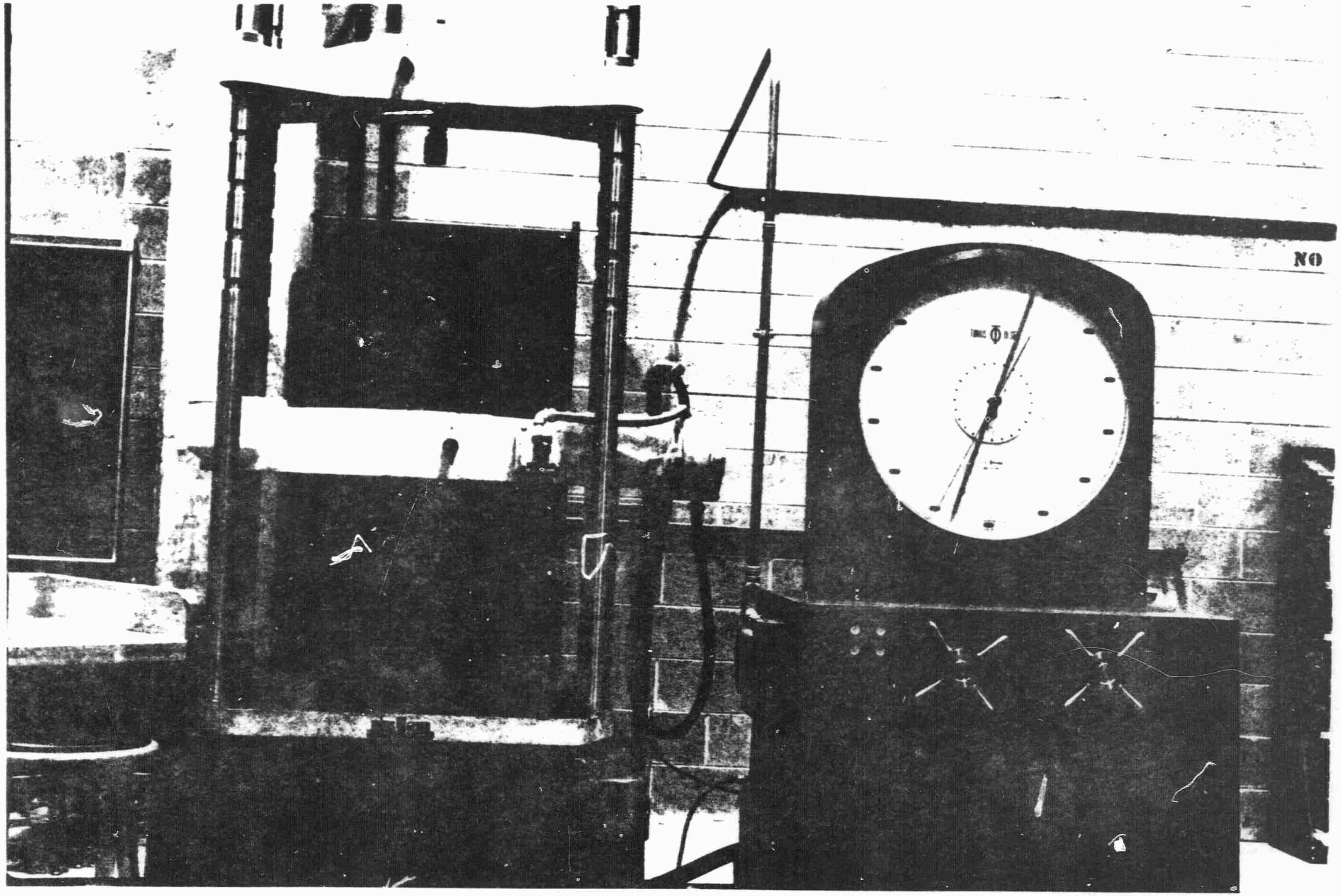
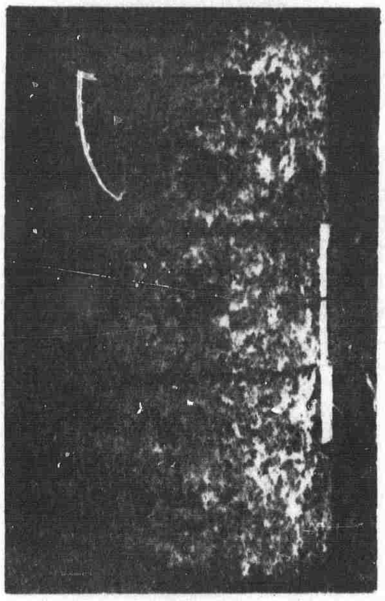
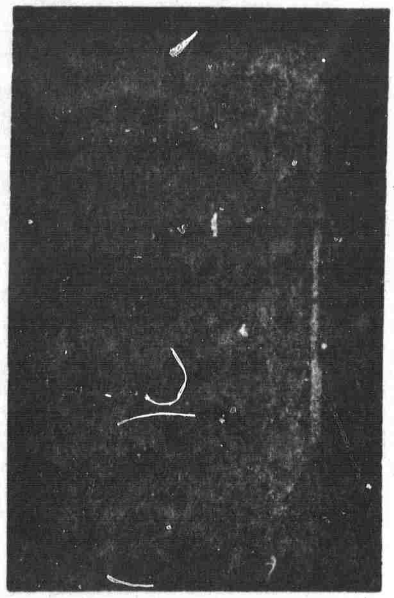


Figure 15 - Equipment for deformation of cylinders. One of three units available for uniaxial deformation of cores. (Tinius-Olson Model 60-D Super "L" Universal testing machine, 60,000 lb. capacity)

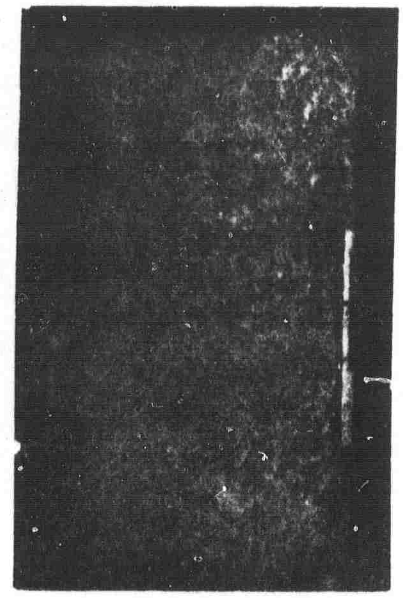
One of the units not shown (Instron TT-D Universal testing maching, 20,000 lb. capacity) is part of a closed-loop, programmable system, with an environmental chamber. The third unit is a Tinius-Olson compression testing maching, 400,000 lb. capacity.



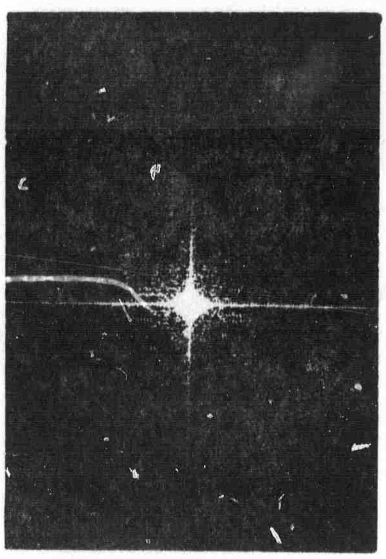
a



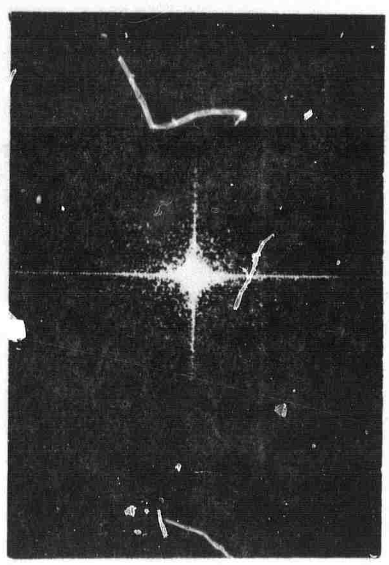
b



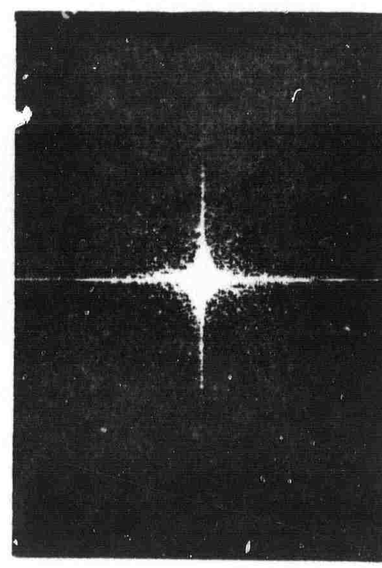
c



A



B



C

Figure 16 - Deformation series and preliminary optical diffraction results. Specimen is cylinder, 1 in. (25.4 mm) x 2 in. (50.8 mm) of St. Cloud gray granodiorite ("Charcoal Gray granite"). Photographs above from three different load levels (top row). Transforms (A), (B), (C) correspond to inputs (a), (b), (c) above. Load curve is linear, with E = app. $11(10)^6$psi ($75.842GN/m^2$).

(a)(A) no load; (b)(B) 3200 psi ($22{,}063kN/m^2$), strain $300(10)^{-6}$; (c)(C) 19,400psi ($133{,}759kN/m^2$), strain $1725(10)^{-6}$.

Largest contrast noted so far in the transforms is between (A) and (B). Results between (b) and (c) not presented here.

APPENDIX B

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